

Title: Large Area Scene Selection Interface (LASSI). Methodology of Selecting Landsat Imagery for the Global Land Survey 2005.

Description: To facilitate the scene selection process for the GLS2005, NASA and the USGS sponsored the development of a new tool to generate optimal collections of imagery using metadata statistics and user-defined weighting criteria.

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Abstract

The Global Land Survey (GLS) 2005 is a cloud-free, orthorectified collection of Landsat imagery acquired during the 2004-2007 epoch intended to support global land-cover and ecological monitoring. Due to the numerous complexities in selecting imagery for the GLS2005, NASA and the U.S. Geological Survey (USGS) sponsored the development of an automated scene selection tool, the Large Area Scene Selection Interface (LASSI), to aid in the selection of imagery for this data set. This innovative approach to scene selection applied a user-defined weighting system to various scene parameters: image cloud cover, image vegetation greenness, choice of sensor, and the ability of the Landsat 7 Scan Line Corrector (SLC)-off pair to completely fill image gaps, among others. The parameters considered in scene selection were weighted according to their relative importance to the data set, along with the algorithm's sensitivity to that weight. This paper describes the methodology and analysis that established the parameter weighting strategy, as well as the post-screening processes used in selecting the optimal data set for GLS2005.

Introduction

Monitoring global changes in land cover is a principal objective of remote sensing science. In order to produce reliable measures of land-cover change and disturbance, researchers require a consistent global baseline set of cloud-free, leaf-on imagery. The Global Land Survey (GLS – formerly known as “Geocover”) data sets provide wall-to-wall, cloud-free Landsat coverage of the Earth's land areas for epochs centered on 1975,

1990, 2000, and 2005. These data sets provide the science and conservation communities a comprehensive view of how the planet's land areas have changed over the past thirty-five years.

The goal of the Global Land Survey 2005² (GLS2005) was to provide one clear Landsat or Landsat-like image during peak vegetation conditions for every location of the global land area during the 2004-2007 period (Gutman *et al.*, 2008). The GLS2005 data set consists of approximately 9,500 Landsat images; an increase compared to the 1990 GeoCoverTM (~7,000 scenes) and the 2000 GeoCoverTM (~8,200 scenes). This increase accounts for additional coastal and island areas not represented in the earlier GeoCoverTM data sets, and the inclusion of the Landsat Image Mosaic of Antarctica (LIMA) that was produced separately in support of the International Polar Year.

GLS2005 was a collaborative effort between NASA and USGS, led by a science steering group with members from NASA headquarters, NASA Goddard Space Flight Center, USGS headquarters, USGS EROS, University of Maryland, Aerospace Corporation, Lockheed Martin, and Emalico LLC.

The primary application of the GLS data sets are to monitor land use and land cover changes over time at a moderate-resolution scale. In the interest of consistency with the previous GLS data sets, the GLS science steering group preferred Landsat data wherever possible. The majority of the global data set would be chosen from available

² The GeoCoverTM 2000 data set has been reprocessed to improve the geometric accuracy and establish a control baseline for GLS2005, the other GeoCoverTM data sets, and current Landsat product generation. After reprocessing, the GeoCoverTM data sets are renamed GLS.

Landsat 5 and Landsat 7 data using the LASSI tool, augmented by manually selecting (ie. Not using LASSI imagery from Earth Observing 1's Advanced Land Imager (EO-1 ALI) imagery and Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) as needed. This not only reflects the diversity of Landsat-like resolution remote sensing satellites in orbit, but also underscores the shortcomings of Landsat: the inability to secure global coverage with Landsat 5 Thematic Mapper (TM), and the failure of the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) Scan Line Corrector (SLC) in 2003 (Gutman *et al.*, 2008).

This paper describes the process of scene selection for the GLS2005 data set. To facilitate the automation of the scene selection process, the GLS2005 project, in collaboration with NASA Ames Research Center, developed a new tool to generate optimal collections of imagery using metadata statistics and user-defined weighting criteria. In the sections below, we describe the parameters used in scene selection, discuss the reasoning behind the weighting of those parameters, talk briefly about the post screening processes, show the results of the scene selection of North America, and discuss lessons learned along the way.

Background

There are three existing global survey data sets: GeoCover™ 1975, 1990, and 2000. These were produced by the EarthSat Corporation (now MDA Federal, Inc.) under contract to NASA. Scene selection for these data sets was based on visual aspects of the imagery, like clouds, haze, missing scan lines, and other manifestations of poor data

quality. Image characteristics were weighed against the year and season in which the data were acquired (Tucker *et al.*, 2004). While scene selection was labor intensive, it was feasible because only a few characteristics were considered, and most of them were assessed quickly mainly by visual inspection. For GLS2005, not only were there more data available, but the task became considerably more complicated due to the failure of the Landsat 7 ETM+ SLC in 2003 (Williams *et al.*, 2006). While there have been other studies that have documented the methods of optimally putting together a Landsat 7 ETM+ large area database (Yang *et al.*, 2001), none of these have addressed the difficulties of gap filling imagery and have considered so many parameters in doing so.

Landsat 7 continues to acquire global coverage, but with the SLC failure each scene is missing approximately 22 percent of its area coverage in cross-track, bow-tie shape that are widest at the scene edges. The most suitable workaround for these missing data in ETM+ images is to “gap fill” the imagery with other imagery from the same growing season. Although this is a credible strategy (Masek, 2007), it magnifies the complexity of the scene selection process. It was necessary to not only select the best base scene for that Worldwide Reference System (WRS) path and row, but also the best associated fill scene. The pair of chosen images are referred to as the “base” and “fill” selections. Occasionally, two fill images were chosen to achieve full geographic coverage of the scene. The added complexities of dealing with gap-filled imagery did raise the question of whether Landsat 7 ETM+ data should be used for the dataset. The GLS2005 science steering group and user community representatives decided that, in situations where the “base” and “fill” scenes were cloud-free and the land cover was not a

seasonally dynamic land cover type such as agriculture, it was preferable to use Landsat 7 “gap-filled” imagery due to its superior geometry and radiometry when compared to Landsat 5 TM.

GLS2005 primarily consists of Landsat 5 TM and Landsat 7 ETM+ imagery with supplemental selections from EO-1 ALI and Terra ASTER image collections. Given the smaller swath-width of the ALI instrument (30km), EO-1 selections were limited to coverage of small islands and reefs. ASTER imagery was used to fill in some problematic regions, such as Northern Eurasia, where no suitable Landsat data were available.

Large Area Scene Selection Interface Tool

Roughly 400,000 Landsat images were considered in scene selection by the LASSI tool for GLS2005. These were reduced to fill 9,500 WRS locations (referred to hereafter as "scenes") based upon criteria that included acquisition date, cloud contamination, gap-fill coverage, sensor choice, and geographic uniformity, as well as other minor factors. To handle the large number of images in the selection pool, and the increased complexities in scene selection for GLS2005, NASA Goddard Space Flight Center (GSFC) and USGS Earth Resources Observation and Science Center (EROS) sponsored the creation of an automated scene selection tool, known as LASSI. At the heart of LASSI is an artificial-intelligence engine called the Global Map Generator (GMG), which was developed by the Computational Sciences Division of NASA Ames Research Center. GMG applies non-linear optimization to identify the “best” collection of scenes based on a user-defined weighting system to pre-determined scene parameters.

The weighting system of the parameters was subjective in nature, but supported by numerous trial and error attempts, along with consultation with the steering group and professionals that have specific knowledge of the region (for example, professionals that work in polar regions recommended to us that imagery that is later in the growing season is more useful than imagery early in the growing season). “Relative importance” was determined in a fashion that would maintain consistency with the goals of the data set. With supplied metadata of all candidate images, GMG quickly and systematically sorts through thousands of images to select the best overall set to form a regional solution. For the sake of simplicity, this paper describes the methods used for establishing the parameter weights specifically applied to the North American continent. For details about the weighting scheme used for the other continents and the results of those selections, please contact the authors directly. For more information on the algorithmic basis for the tool, see Khatib *et al.* (2007).

Selection Parameters

Description

During scene selection, there were 14 parameters considered by LASSI. The weight of each parameter was set by the LASSI operator to reflect its significance for scene selection for a particular region. These factors and their associated weightings drove the scene selection. All Landsat 7 imagery required image pairs to provide complete coverage. A “base” image covers approximately 78 percent of the WRS scene area. The

“fill” image is chosen to furnish coverage of some or the entire remaining 22 percent gap left by the base image. Fill image parameters apply only to Landsat 7.

- NDVI- base Image: Phenological Normalized Difference Vegetation Index (NDVI) of Landsat 5 (L5) image or Landsat 7 (L7) base image, temporally interpolated from a mean monthly NDVI record. For this factor, the Pathfinder (PALS) AVHRR NDVI time series was used after sub-averaging 8km resolution monthly values to the area of each WRS scene (James and Kalluri, 1994).
- NDVI- fill Image: NDVI of the L7 fill image.
- ACCA- base Image: The Automated Cloud Cover Assessment (ACCA) score is generated during L7 image processing and reports the percentage of clouds present in the L7 imagery at a precision of 1% cloud cover. The L7 ACCA algorithm is an unsupervised classifier that detects and reports clouds based on the known spectral properties of clouds (Irish *et al.*, 2006). L7 “ACCA clouds” are defined as optimally thick or opaque, and does not include semi-transparent clouds such as Cirrus, nor artifacts such as cloud edges or shadows. The cloud score algorithm for L5 results in a coarser estimate (10% cloud cover increments). For GLS2005, all L5 imagery was manually prescreened to only consider cloud-free images. Increasing this weight favored clear ETM+ base imagery or clear TM images.
- ACCA- fill Image: ACCA score for L7 fill image.

- Difference in Acquisition Dates between L7 gap-filled pairs: Increasing this parameter favored L7 base/fill pairs with minimal seasonal difference between them. As a side effect, this favors L5 imagery because the “date difference” is zero. This factor was influential in regions where vegetation changed rapidly, such as agricultural fields or regions with short growing seasons.
- Difference in Acquisition Dates between L7 gap-filled pairs (over agriculture): This parameter worked in conjunction with the previous one, but was applicable only for scenes containing a significant area of agriculture, as defined by the MODIS landcover product, MOD12 (LPDAAC, 2001). In essence, it increased the effect of the parameter “Difference in acquisition dates between L7 gap-filled pairs”, scaled to the percent of the scene agriculture area. An example of this parameter’s influence can be found in the section detailing parameter weighting.
- Area coverage: This factor influenced how much of the scene area was covered by Landsat imagery. An L5 image always covers 100 percent of the scene area. A single L7 image only covers 78 percent of the area, but a composite of two L7 images achieves between 78% and 100% coverage. Increasing this factor drove LASSI to select L7 image pairs that achieved as close to 100 percent coverage as possible, or to select an L5 image instead.
- Difference in Day of Year between North-South neighbors: This parameter weighted the preference of choosing images in adjacent north-south scenes taken at the same time of year, irrespective of the specific year. Optimizing

this factor resulted in more compatible seasonality among neighboring scenes in the north-south direction.

- Difference in Day of Year between East-West neighbors: Same as the above parameter, but applied to the east-west neighboring scenes.
- Preference Landsat 5 Imagery: Increasing this parameter favored LASSI selection of L5 imagery.
- Preference Landsat 7 Imagery: Increasing this parameter favored LASSI selection of L7 imagery.
- Sensor Homogeneity: Increasing this parameter favored contiguous spatial groups of a single sensor (L5 or L7). It is this parameter, along with the Difference in Day of Year between the North-South and East-West neighbors that encouraged uniformity of the resultant data set.
- Preference toward a Specific Date Range: For GLS2005, it was desirable to select images acquired during the middle of the decade (2005 and 2006) as opposed to 2004 and 2007. Increasing the weighting of this parameter influenced that decision.
- Preference Day of Year: This parameter applies a preference toward selecting images from the same time of year as the GeocoverTM 2000 data set. This facilitates change-over-time research between the two datasets.

Parameter Weighting (with Metadata Visualizations)

Table 1 shows the weighting values used for the North American continent scene selection. The scene selection for other continents used slightly different weights to adapt

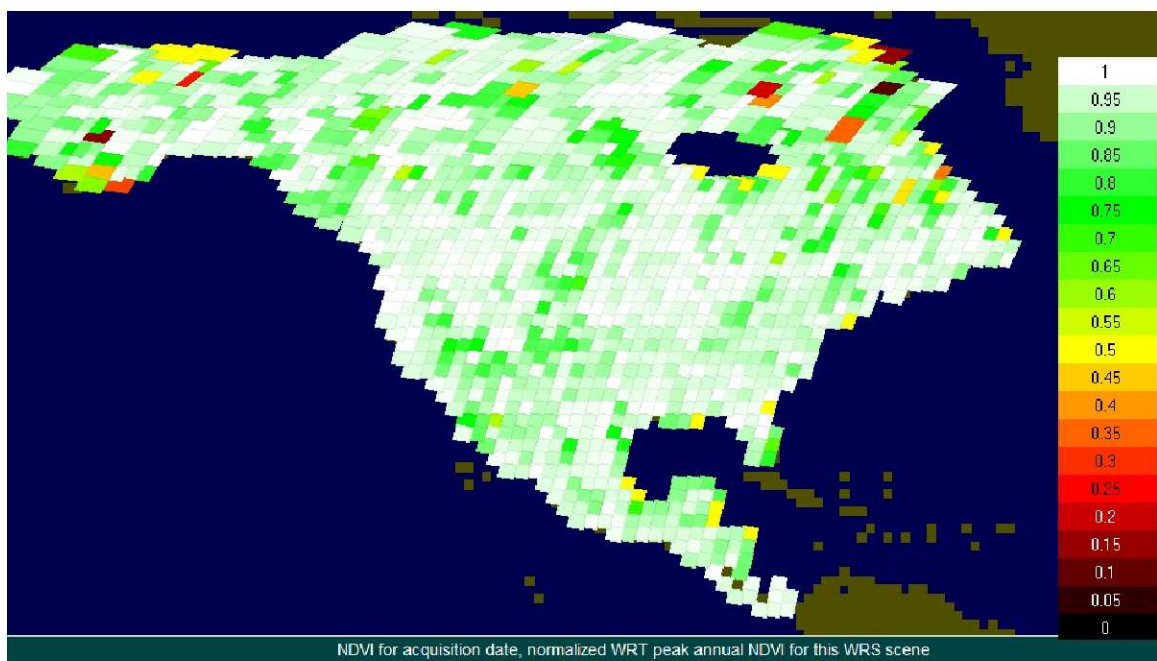
to the differing characteristics of those regions. The numerical values are unitless and simply express the relative weights assigned to various data set characteristics (explained below).

Table 1. Parameter weightings used for North America scene selection for GLS2005.

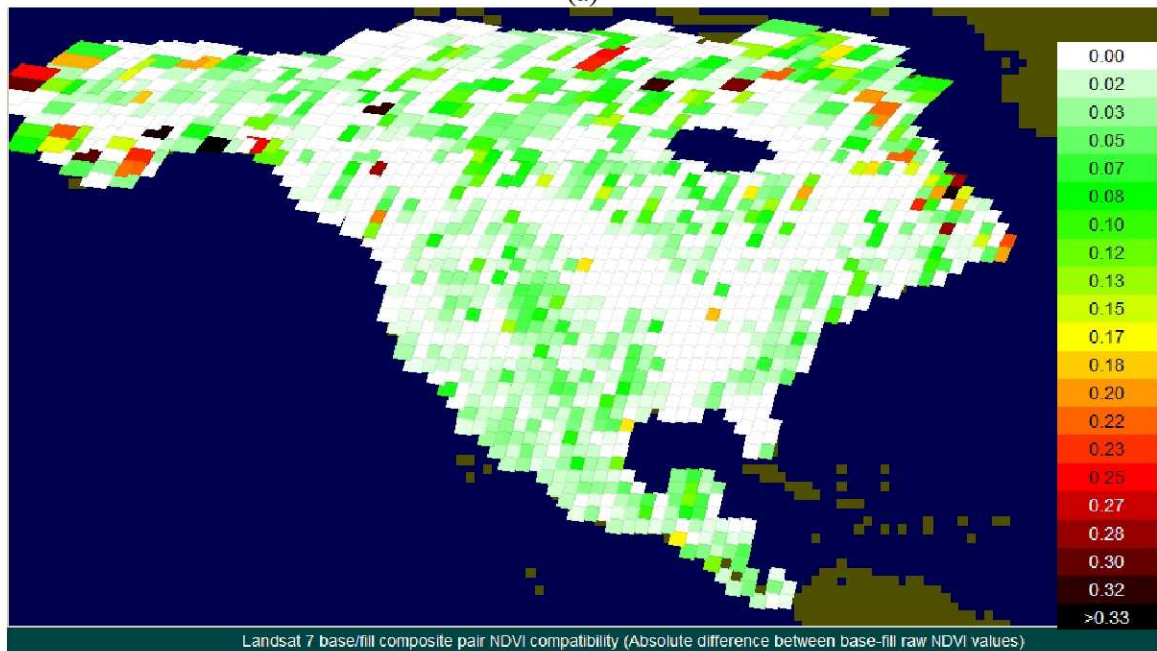
Parameter	Value	Description
NDVI_B	60	NDVI – base image
NDVI_F	30	NDVI – fill image
ACCA_B	20	ACCA – base image
ACCA_F	20	ACCA – fill image
difAD_P	10	Difference in acquisition dates between L7 gap-filled pairs
difAD_P (ag)	40	Diff. in acquisition dates between L7 gap-filled pairs (over agriculture)
Coverage_P	15	Area coverage
difDY_NS	4	Diff. in day of year between N-S neighbors
difDY_EW	4	Diff. in day of year between E-W neighbors
L5_pref	0	Preference L5 imagery
L7_pref	10	Preference L7 imagery
SensHomg	5	Sensor homogeneity
Date_pref	10	Preference towards a specific date range (2005 and 2006)
DOY_pref	15	Preference day of year (Geocover 2000 TM)

NDVI - base and fill Images

Maximizing the NDVI of the base and fill images was given the greatest weight, since imagery at the peak of the growing season is critical for land-cover and land-use change analysis, which is the principal use of the GLS data sets. Plate 1a depicts the NDVI values, which have been scaled to represent the percent of maximum NDVI for each scene. By displaying the map as percent of maximum made it easier to determine if the parameter was successfully optimized. Normalizing the values facilitated comparison of scenes with a low NDVI average (e.g., deserts) and scenes of high average NDVI. The fill image was also strongly weighted to minimize the differences between the NDVI values of the Landsat 7 gap-filled image pairs, as shown in Plate 1b. This also ensured that both images were acquired within the same growing season. The average absolute NDVI for the base (Landsat 7 and Landsat 5) images was 0.560. In Plate 1, white is ideal, and light-green is acceptable.



(a)

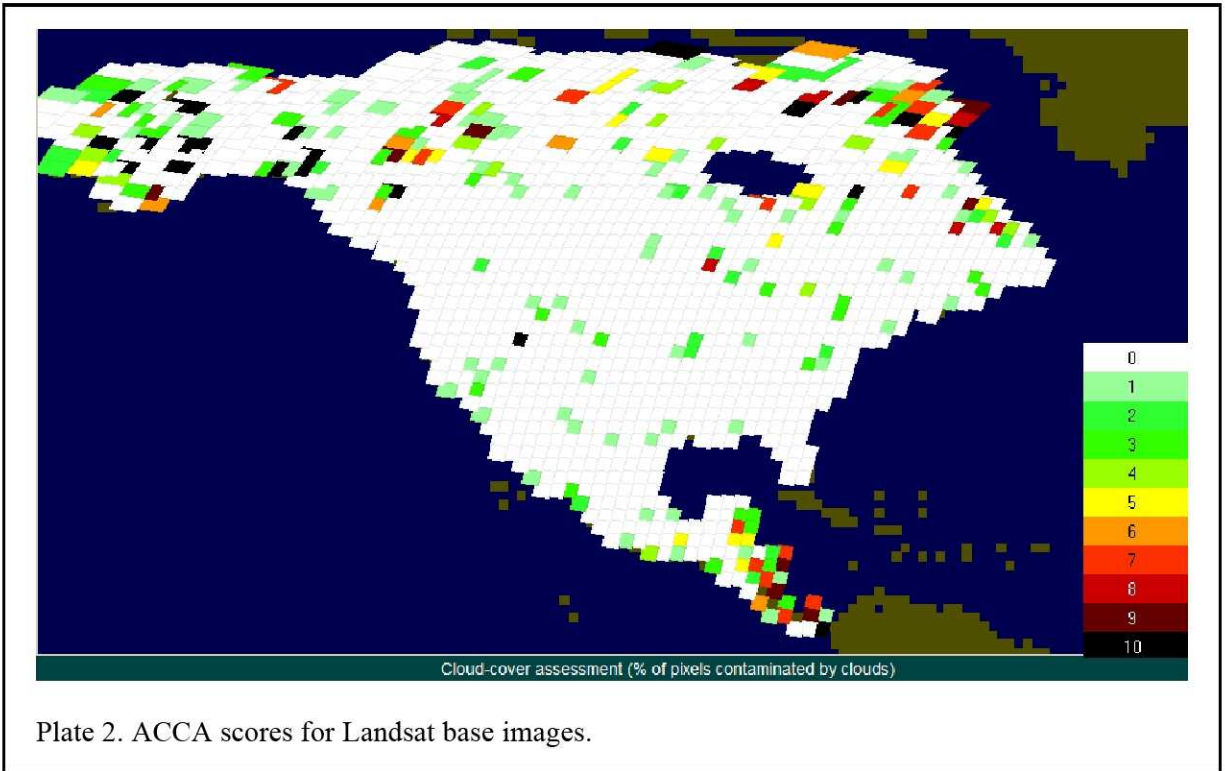


(b)

Plate 1. (a) NDVI of base imagery normalized to the percent of maximum NDVI for each WRS scene and (b) Difference of NDVI between Landsat 7 image pairs. Landsat 5 images have a difference NDVI of 0.

ACCA- base and fill Images

ACCA for the base and fill images was not heavily weighted because the input images were initially filtered such that LASSI was selecting from a pool of imagery known to have 10 percent or less cloud cover. Previous research showed that gap-filling of Landsat 7 imagery yielded acceptable end products when both the base and fill images are cloud-free (Masek, 2007). When either the candidate base or fill image contained clouds, the histogram matching between the images resulted in the cloud radiometry contaminating the pixels of the accompanying image. This research led to the general requirement that the base image be restricted to 4 percent or less cloud cover and the corresponding fill image to 8 percent or less. If either of those thresholds was exceeded and no alternative was available, the chosen base and fill images were not processed as gap-filled composite pairs in the final data set; rather, they were included in the final data set as individual images. The average cloud cover of the data set was extremely low, with less than 1 percent clouds (0.757 ACCA) in the base imagery (Plate 2) and a 1.7 ACCA in the fill imagery.



Difference in Acquisition Dates between Landsat 7 gap-filled pairs

In most cases, the difference in acquisition dates between Landsat 7 gap-filled pairs was less important as the difference of NDVI in Landsat 7 pairs. Properly weighting the NDVI parameters between base and fill (NDVI_B, NDVI_F) also minimized the base-fill temporal difference as well. For that reason, the difAD_P parameter was weighted lower with a value of 10. However, in regions of rapid change, such as croplands, the temporal difference was not sufficiently minimized using NDVI alone. For these regions, scenes acquired several cycles apart were not acceptable due to the resulting phenological differences. To address this concern, we introduced a second parameter specific to agricultural scene composition (difAD_P(ag)) to influence the weighting applied to the

original difAD_P parameter as a function of the percentage of cropland in each scene. We used the MODIS land cover product MOD12 to discriminate areas of agriculture and from that compute the percentage of each WRS scene area containing cropland. After some trial runs, we assigned a value of 40 to the new parameter. Over most regions of the globe where the area of classifiable agriculture is inconsequential, the difAD_P (ag) parameter had no impact, as shown in equation (1) below. But this factor became relevant in parts of the world where agriculture was a sizeable constituent of a scene. For example, if a given scene consists of 80 percent croplands, the total addition of the two difAD_P parameters would be 42, as shown in equation (2). See Plate 3 for the temporal difference between Landsat 7 pairs in the North America selected data set.

$$(1) \quad 10 + 0.0(40) = \mathbf{10}$$

$$(2) \quad 10 + 0.8(40) = \mathbf{42}$$

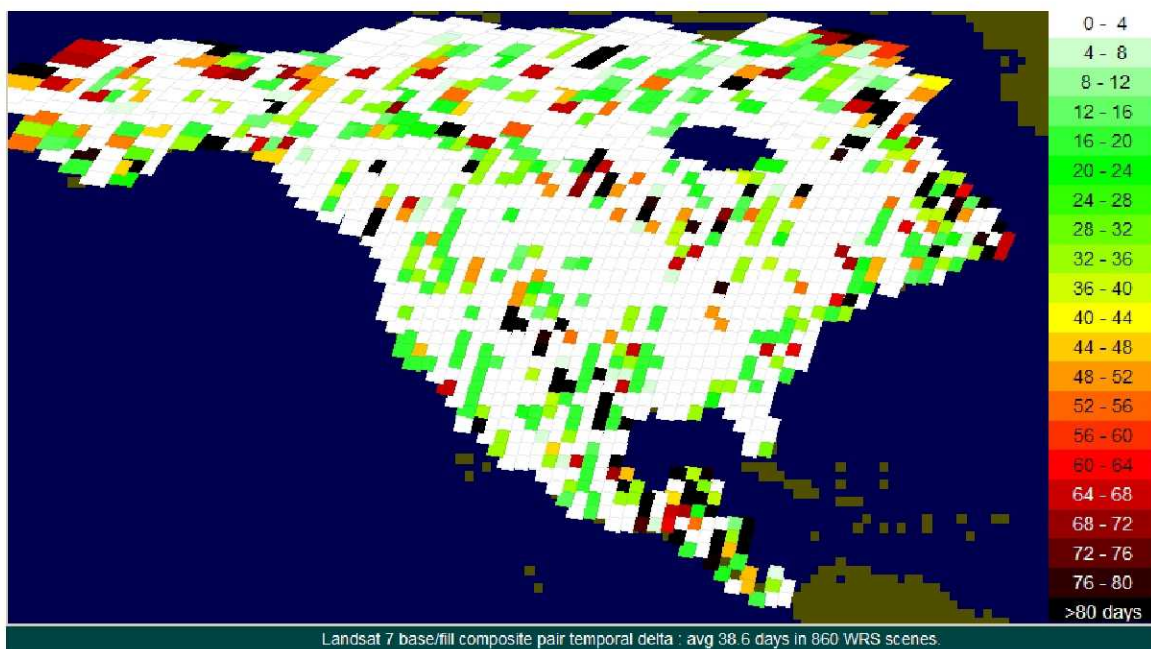
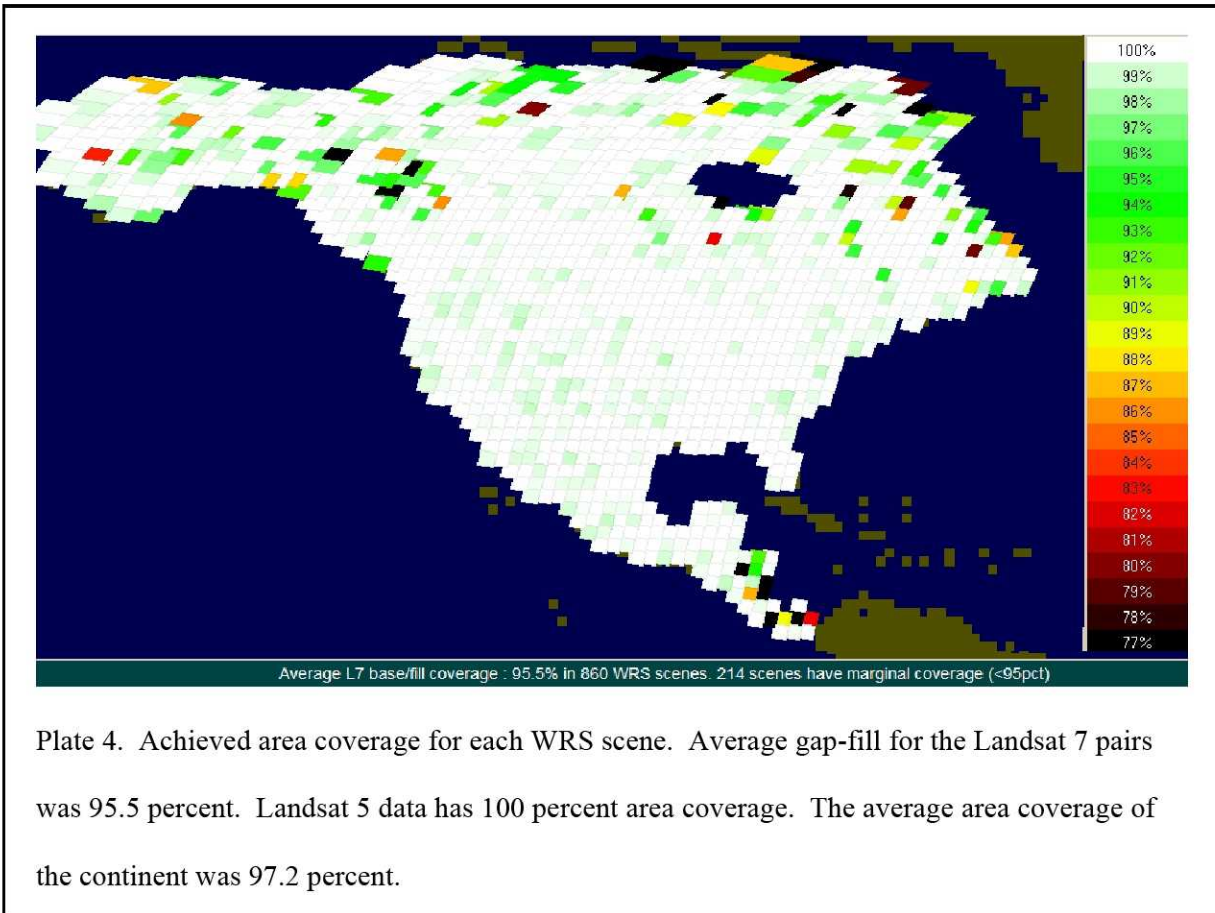


Plate 3: Temporal difference between Landsat 7 pairs (Landsat 5 images have a value of 0, since the data is not gap filled with another image). The small temporal difference in the croplands belt is the result of the agricultural parameter. Overall, the average temporal difference between Landsat 7 image pairs was 39 days.

Area Coverage

The gap-fill goal for GLS2005 was to have at least 95 percent area coverage by each ETM+ base-fill composite pair (Plate 4). Complete area coverage was easy to achieve in areas with a rich pool of candidate images, but was more challenging where the candidate pool was shallow. To attain adequate coverage, on rare occasions it was necessary to manually add a second fill image to augment a base-fill pair chosen by LASSI. Area coverage was most often at odds with the difference in NDVI, where the best NDVI match did not always fulfill the area coverage requirement. In these situations we

decided to include the two images that were seasonally consistent and try to again supplement the outstanding area coverage with the addition of a second fill image.



Difference in Day of Year for East-West and North-South Neighbors

The Difference in Day of Year for East-West and North-South Neighbors parameters were useful to minimize the seasonality differences between neighboring paths or rows, but not as important to data set quality as some of the other parameters. This attribute was an effective tie-breaker where the candidate pool of imagery was deep, such as in North

America, when all other factors were roughly equal. The North-South effect was not satellite-specific. However, the East-West effect could result in one path consisting mainly of Landsat 5 imagery and the next path consisting mainly of Landsat 7 data, due to the 8-day revisit frequency between the two satellites as compared to the standard 16-day satellite revisit cycle of each individual satellite. To counter this effect, we programmed LASSI to consider two scenes taken within 16 days to be of equal value in this domain.

Sensor Preference

Landsat 7's superior radiometric and geometric properties led to a slight preference for using Landsat 7 imagery over Landsat 5 imagery. For North America, we weighted only the Landsat 7 parameter, at a low value of 10, so that it became a "tie-breaker" when LASSI had both a suitable Landsat 7 image pair and a suitable Landsat 5 image for the same scene. As shown in Plate 5, LASSI predominantly selected Landsat 7 imagery (63 percent) except in the agriculture belt of the United States, where the temporal difference between the Landsat 7 base and fill images was often unacceptable.

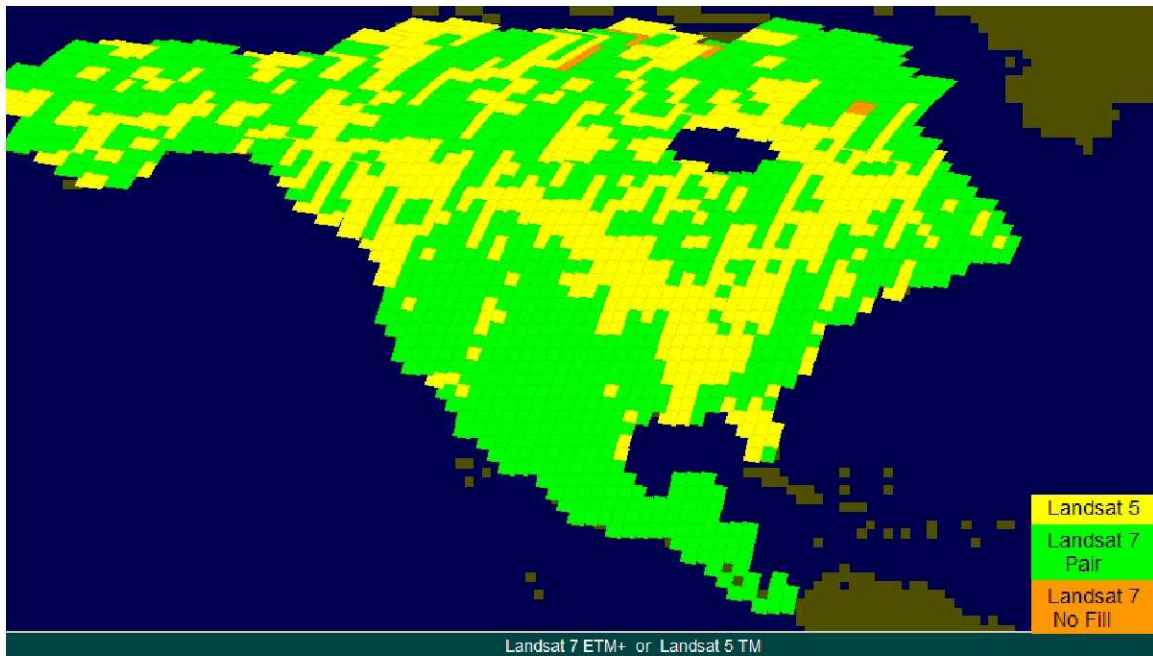


Plate 5. Sensor selection for the North American continent, influenced by both the Landsat 5/Landsat 7 preference parameters and the sensor homogeneity parameter. The Landsat 7 No Fill category also indicates no acceptable Landsat 5 availability.

Sensor Homogeneity

In general, a preference was given for acquiring data from a single sensor (L5 or L7) across a geographic neighborhood. Given the majority of Landsat 7 selections, as discussed in the previous paragraph, the Sensor Homogeneity further emphasized Landsat 7. We weighted this parameter with a low value (5) because it optimized very easily in scene selection, and we did not want it to dominate other parameters more important for data set quality. As can be seen in Plate 5, the selection was spatially

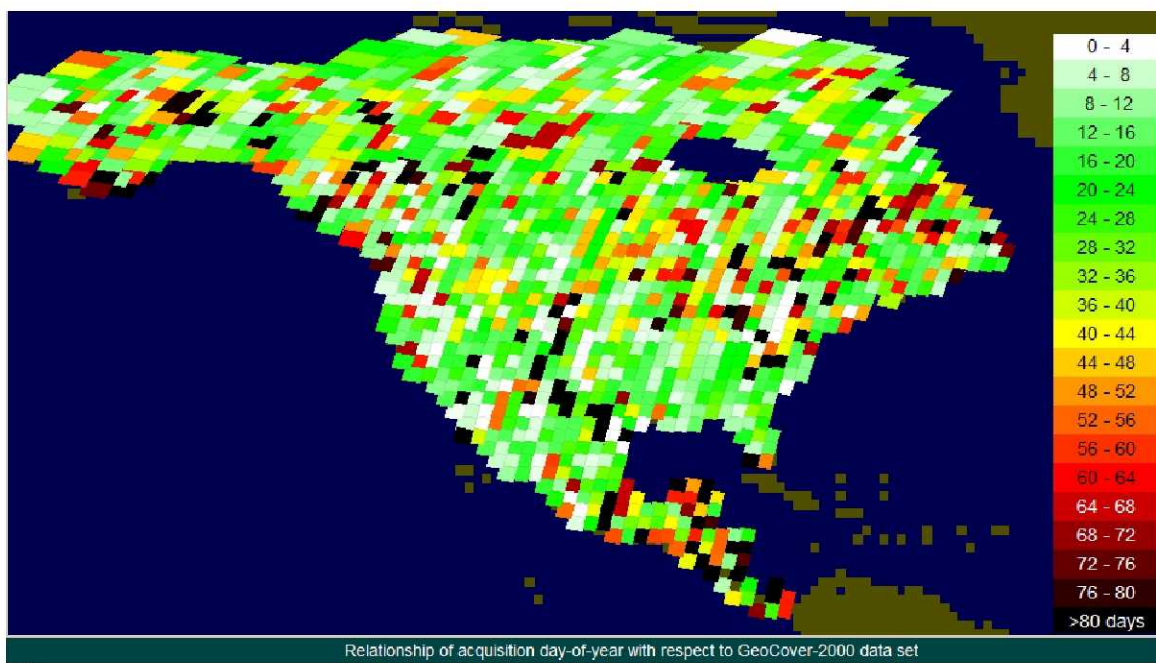
grouped by sensor, rather than the “salt and pepper” effect wherein Landsat 5 and Landsat 7 images are intermixed.

Preference towards a Specific Date Range

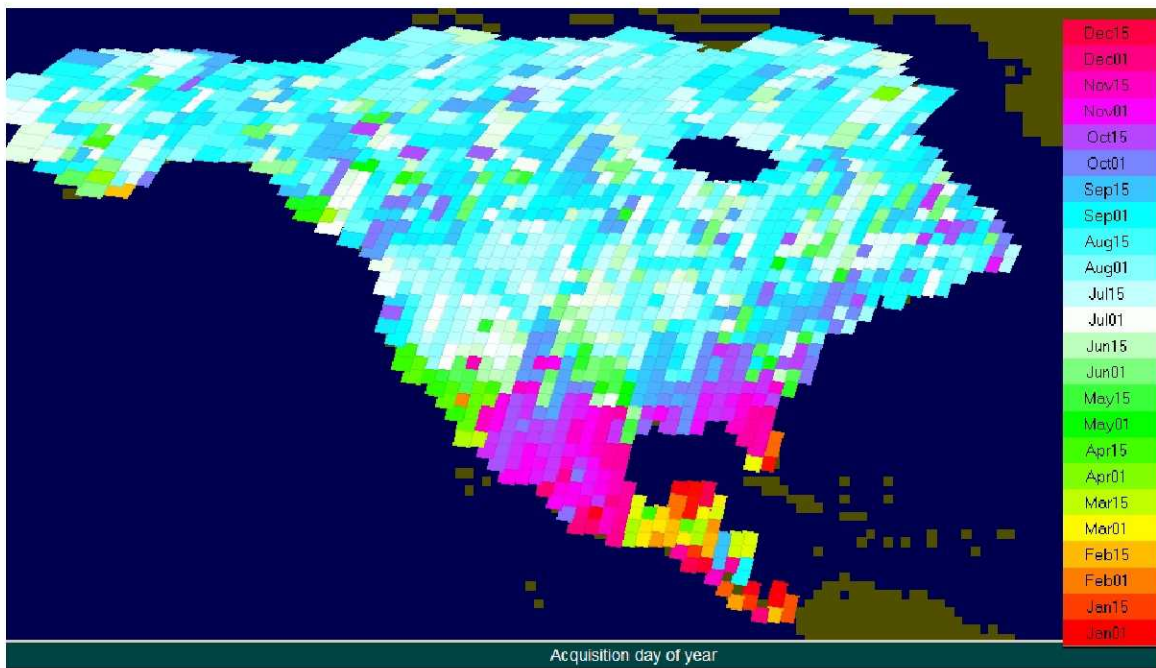
A large majority of the scenes had acquisition dates in one of the two preferred study years: 2005 or 2006. This was not considered a driving requirement, so the Preference towards a Specific Date Range parameter was assigned a low value. The percentages of scenes collected in each year were: 2004: 11.5 percent, 2005: 39.8 percent, 2006: 39.7 percent, and in 2007: 9.0 percent.

Preference Day of Year

This factor applied a preference on selecting images with acquisition dates close to the GeocoverTM 2000 data set. For land-cover and land-use change (LCLUC) analysis, matching acquisition days of year would facilitate trending studies using the GeoCoverTM 2000 and GLS2005 data sets. However, the time of year selected for the GeocoverTM 2000 images was not always optimal, with many acquired late in the growing season to avoid cloud cover (Tucker et al., 2004). Weighting this parameter for GLS2005 balanced between selecting images that were temporally similar to GeocoverTM 2000 while avoiding the possible quality degradation set by doing so. Our analysis showed that a weight of 15 sufficiently satisfied this goal. The resulting temporal differences are shown in Plate 6a, and Plate 6b depicts the GLS2005 selected day of year.



(a)



(b)

Plate 6. (a) Difference in days between acquisition dates for GeoCover™ 2000 and GLS2005 selected base images, and (b) GLS2005 base image acquisition day of year.

Post-Selection Screening

Although LASSI is a powerful tool for scene selection, manual visual inspection was necessary to verify the quality of the data set. The LASSI interface supports post-selection screening by displaying a mosaic of thumbnail browse images of the selected base images (Plate 7a). Hovering the cursor over a WRS scene cell brings up the base and fill images side-by-side, along with their respective metadata, and a scrollable row of other candidate images for that scene that were not selected.

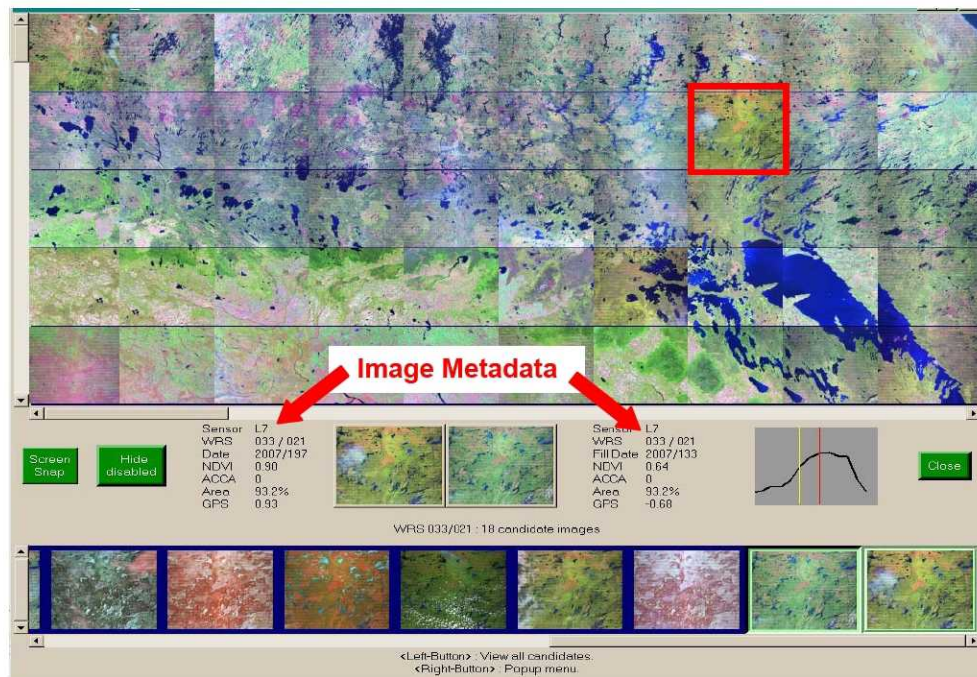
Visual inspection was performed following automated scene selection of each continent to identify non-optimal selections and obvious outliers. While LASSI selected the large majority of images, visual inspection was necessary to confirm those selections. The operator was able to manually override LASSI's automated selections where needed when imperfections were visible in the browse imagery that were not evident in the metadata. In many of these cases, the ACCA algorithm did not detect prevalent cirrus clouds, haze, or forest-fire smoke, which is a known limitation of the algorithm (Irish et al., 2006). Additionally, because the modeled NDVI did not always fit annual seasonal variation, visual inspection also identified those selections that were either too early or too late in the growing season.

Plate 7a illustrates the case of a non-optimal base selection (highlighted in red) identified during the post-selection screening. Although LASSI made the proper decision based solely upon the metadata information of the base image (left) and fill image (right), and the assigned weighting factors, visual inspection reveals cloud or smoke contamination in the western side of the scene that was not accounted for in the ACCA

score (zero). The other candidate images, shown at the bottom of the screen, are all either leaf-off winter images or have considerable cloud cover. Accepting that the original pairing was the best selection, the operator elected to swap the base and fill selections, using the slightly contaminated image as the fill instead of the base to yield a better gap-filled composite product.

The post screening process also involved assessing image selections that appear to be outliers in the metadata visualization maps. Plate 4 offers a good example of this. The scene directly below Hudson Bay, Canada, looks suspicious because all of its neighboring scenes have acceptable area coverage, but this one scene (in red) has an area coverage of only 82.5 percent. Plate 7b presents a closer look at the chosen images and the shallow pool of candidates for this scene. Three of the five candidates were winter scenes with very low NDVI. Since NDVI was the most heavily weighted parameter, LASSI chose the pair of images with higher NDVI, trading against low area coverage. There were no other satisfactory choices. In this example, it was preferred to choose a Landsat 7 ETM+ image pair with low area coverage but with a similar stage of growth, than to have a pair with high area coverage but taken in incompatible seasons. In this case LASSI selected the correct pair, and no manual adjustment to the selection was made.

(a)



(b)

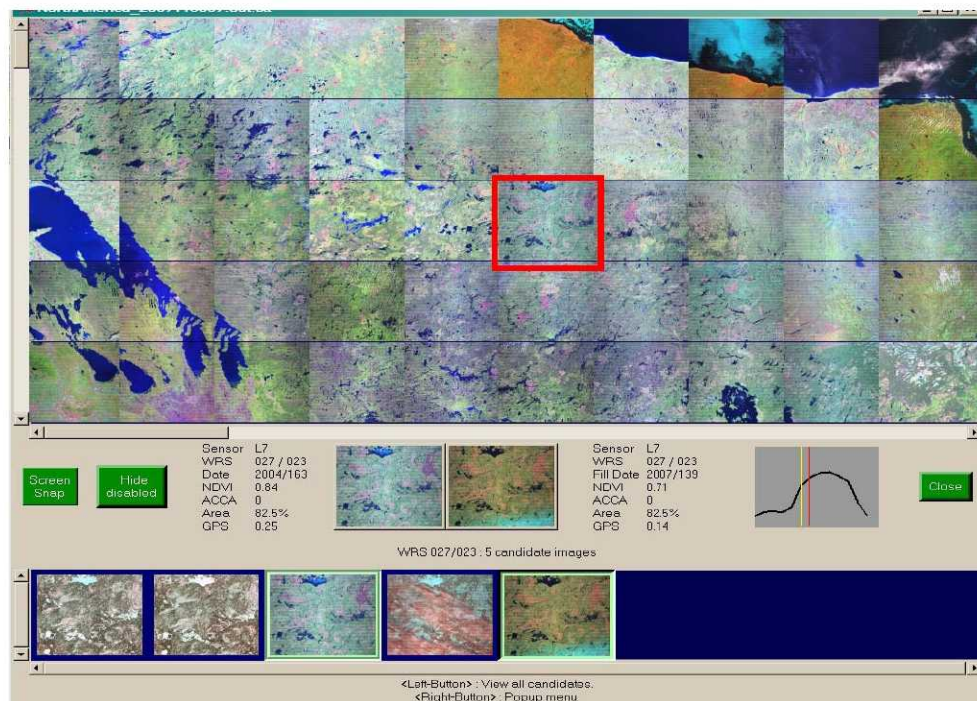


Plate 7 (a) LASSI post-screening interface showing an example of non-optimal base-fill assignment, where “flipping” the LASSI assignments would result in a better gap-filled product and (b) LASSI post-screening interface showing a selection that had low area coverage. There was no correction to the LASSI selection due to the lack of other leaf-on images.

At times, the operator had to choose between two very similar images. If the modeled NDVI (based on the date of acquisition) of both images was similar, then they were visually analyzed to determine which one was in a higher stage of seasonal green-up. If, after that examination, the decision was still not clear, the inspector would select the one that was later in the season, especially in the northern regions of Canada and Alaska where the growing season has a slow start due to ice melt-off in the spring.

Special cases and exceptions

Processing Landsat 7 images pairs is very common – almost 40 percent of all recent Landsat 7 sales use multiple images. However, the processing of over 9,000 scenes for GLS2005 has given an unprecedented view into the nuances of scene selection for SLC-off image pairs. Areas of persistent clouds during the growing season proved extremely problematic for scene selection, even given the depth of the U.S. archive. The scene selection task for the North American continent provided many lessons learned. The following sections discuss special cases and exemptions encountered during the selection and subsequent screening processes.

Landsat 7 ETM+ bumper mode transition

On April 1, 2007, the Landsat 7 ETM+ instrument transitioned from Scan Angle Mirror (SAM) mode to Bumper Mode. This change of operations occurred when the ETM+ scan mirror bumper wear exceeded the specifications for SAM mode operation. Bumper mode resulted in an immediate, significant increased scan-time length, which made it impossible to form a composite product from images taken in these two incompatible

modes. To avoid data processing problems, a rule was added to LASSI disallowing an image collected prior to April 1, 2007 to be matched with an image collected after that date.

Gap phase drift

Biophysically, images acquired more than two years apart could be matched as Landsat 7 pairs as long as they were seasonally consistent. However, after processing some of these image pairs, the resulting composite product was consistently falling below the predicted area coverage. As mentioned above, the scan mirror bumpers on the Landsat 7 ETM+ have worn in a linear pattern since launch. As the bumpers wore over time, the ETM+ mirror scan period lengthened. If images were acquired more than 16 months apart, there was too great of an offset between images to process them to the predicted area coverage. As a result, the Difference in Acquisition Date between pairs (difAD_P) parameter should have been weighted much higher to preclude the matching of images from dates that were too far apart. After learning this lesson, we enhanced LASSI to compute a more precise estimate of area-coverage considering the age difference between a candidate pair in the computation. Thereafter, LASSI's automated picks were considerably improved.

Only one Landsat 7 scene with ACCA <10 percent

The image pool from which LASSI made its selections was initially constrained to those with ACCA scores of 10 or less. As a consequence, twelve scene locations in North America only offered one ETM+ image in the pool, making image pairings impossible.

In this situation, we searched outside of LASSI, using one of the USGS’s satellite imagery search engines, such as GloVis or EarthExplorer, to find the best matching second image that was consistent with the selection criteria (other than ACCA). Because the resulting image pairs exceeded the established cloud-cover thresholds—4 percent for the base image, 8 percent for the fill image—they were not gap-filled, but rather provided as multiple single image selections in the GLS2005 data set. We considered area coverage and the other selection criteria during the search, so as not to preclude gap-filling of these images by the end-user, if desired. We were able to find a pairing image for all but 5 of the 12 locations, as shown in Plate 5.

No cloud-free image

In even fewer cases, there were Landsat path/rows that had no data with less than 10 percent cloud cover. For these locations, manual selection of either Landsat 5 or Landsat 7 was performed to achieve as much cloud free area coverage as possible. However, in this case, more than two images were chosen (base and two fill images) to obtain clear coverage with Landsat 7 data. These selections were provided as single images, rather than gap-filled.

Imperfect gap-filling result

Analysis of the gap-filled products for GLS2005 concluded that most were of good quality—it was impossible, in most cases, to detect seams in the gap-filled radiometry. However, there were a few scenes that, when gap-filled, showed “contamination” in the base layer from the fill layer. We were aware of this problem when gap-filling images

with some cloud cover, but we found the situation also applied to scenes with snow, haze, or smoke, none of which was called out in the metadata considered by LASSI. Many of these occurrences were in northern Canada where only one image in a selected pair was free of snow or ice. This also occurred in areas contaminated by smoke from large fires. Since it was obvious that Landsat 7 gap-filled imagery would not be adequate, and there were no Landsat 5 cloud-free candidates, we applied a three-tier strategy for accepting other imagery:

1. Consider Landsat 5 imagery that had as little cloud cover as possible.
2. Relax the temporal requirement for Landsat 5 TM and Landsat 7 ETM+ imagery to allow imagery from as early as late-2003.
3. For high-latitude scenes, where there is substantial overlap from its easterly and westerly neighbors, substitute acceptable imagery from east and west adjacent paths when they entirely covered a problematic scene.

This approach was applied as a last resort when there was no acceptable choice of imagery available. While this alternative strategy was needed in certain scenes, it was only applied to less than 1% of the North America selections as a consequence of the deep archive of candidate imagery of this continent.

Coastal and non-continental land scenes

The LASSI tool is highly dependent on NDVI and cloud cover estimates. NDVI is often not available for scenes with small islands. Additionally, cloud-cover estimates made on a full-scene basis can be misleading in scenes where land is present in only a small part of the scene, such as islands and coasts. For these reasons, islands were excluded from LASSI's automated scene selection and were instead manually selected. Coastal scenes selected by LASSI were visually inspected with extra scrutiny.

Conclusions

Using an automated approach (LASSI) to select the imagery for GLS2005 was an advance over the three previous global surveys. With the increased complexity of GLS2005 scene selection due to a multi-sensor approach, and challenges associated with gap-filling requirements, scene selection without the use of a computer algorithm would have been extremely labor intensive. Although using the LASSI tool dramatically eased this complex process, human input and guidance was still necessary to set the parameter weights, review the results, and manually intervene to override some selections.

Learning the tendencies of the algorithm in order to properly weight its selecting parameters was an effort within itself and took time to set the weighting scheme to obtain the “optimal” result for each continent or biome. There will be situations where users would prefer a different image for their applications or studies, for example imagery that is not at peak-greenness, but this is always a limitation of a single data set.

Overall, employing LASSI has enabled us to select a data set that is phenologically superior to any other Global Land Survey. Previous GLS data sets were conceived as single-sensor data sets (e.g. Landsat MSS for GLS1975, Landsat 5 TM for GLS1990, and Landsat 7 ETM+ for GLS2000). By expanding the available data sources to include Landsat 5 and 7, as well as ASTER and EO-1, the GLS2005 had a richer selection of imagery to choose from. In addition, previous GLS data sets emphasized cloud-free coverage, sometimes at the expense of obtaining leaf-on seasonality. Consequently, for some regions (e.g. dry deciduous tropics) the GLS1990 and GLS2000 data are not always useful for mapping land cover conditions. By fine tuning the weighting criteria within LASSI we have successfully balanced seasonality with cloud-clearing.

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References

- Gutman, G., R. Byrnes, J. Masek, S. Covington, S. C. Justice, S. Franks, and R. Headley, 2008. Towards monitoring land cover and land-use changes at a global scale: The Global Land Survey 2005, *Photogrammetric Engineering & Remote Sensing*, 74(1).
- Irish, R.R., J.L.Barker, S.N. Goward, and T. Arvidson, 2006. Characterization of the Landsat 7 ETM+ Automated Cloud-Cover Assessment (ACCA) Algorithm, *Photogrammetric Engineering & Remote Sensing*, 72(10):1179-1188.
- James, M. E. and S. N. V. Kalluri, 1994. The Pathfinder AVHRR land data set: An improved coarse resolution data set for terrestrial monitoring, *International Journal of Remote Sensing, Special Issue on Global Data Sets* 15(17):3347-3363.
- Khatib, L., J. Gasch, R. Morris, and S. Covington, 2007. Local Search for Optimal Global Map Generation Using Mid-Decadal Landsat Images, *Proceedings of AAAI Workshop on Preference Handling for Artificial Intelligence*, Vancouver, BC.
- LPDAAC, 2001. MODIS/Terra Land Cover Types Yearly L3 Global 0.05Deg CMG MOD12C1, URL: <http://edcdaac.usgs.gov/modis/mod12c1v4.asp>, U.S. Geological Survey (USGS) Center for Earth Resources Observation and Science (EROS), Sioux Falls, South Dakota (last date accessed: 2 September 2008).
- Masek, J.G., 2007. White Paper on Use of Gap-Filled Products for the Mid-Decadal Global Land Survey (MDGLS), URL:

http://lcluc.umd.edu/mdgls/documents/MDGLS_gapfill.pdf (last date accessed: 2 September 2008).

Tucker, C.J., D. Grant and J. Dykstra, 2004. NASA's global orthorectified Landsat data set, *Photogrammetric Engineering & Remote Sensing*, 70:313-322.

Williams, D.L., S. Goward, and T. Arvidson, 2006. Landsat: Yesterday, Today, and Tomorrow, *Photogrammetric Engineering & Remote Sensing*, 72(10):1171-1178.

Yang, L., C. Homer, K. Hegge, C. Huang, B. Wylie, and B. Reed, 2001. A Landsat 7 Scene Selection Strategy for a National Land Cover Database, *Proceedings of the IEEE 2001 International Geoscience and Remote Sensing Symposium* (Sydney, Australia), unpaginated CD-ROM.